A HYBRID HAPTIC STIMULATION PROSTHETIC WEARABLE DEVICE TO RECOVER THE MISSING SENSATION OF THE UPPER LIMB AMPUTEES

MOHAMMAD NAJEH NEMAH

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Faculty of Mechanical and Manufacturing Engineering
Universiti Tun Hussein Onn Malaysia

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DEDICATION

To the lighthouse of science, Great Prophet Mohammad peace be upon him.

To my family, wife, and sons, Ameer and Laith (Nunu). You have given me a lifetime of love, support, and laughter. You are all God-sent and enrich my life.

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ABSTRACT

A hybrid haptic feedback stimulation system that is capable in sensing the contact pressure, the surface texture, and the temperature, simultaneously, was designed for a prosthetic hand to provide a tactile sensation to amputation patients. In addition, the haptic system was developed to enable the prosthetic's users to implement withdrawal reflexes due to the thermal noxious stimulus in a quick manner. The re-sensation is achieved by non-invasively stimulating the skin of the patients' residual limbs, based on the type and the level of tactile signals provided by the sensory system of the prostheses. Accordingly, three stages of design and development were performed to satisfy the research methodology. A vibrotactile prosthetic device, which is designed for the detection of contact pressure and surface texture in upper extremity, represents. While, the design of a novel wearable hybrid pressure-vibration haptic feedback stimulation device for conveying the tactile information regarding the contact pressure between the prosthetic hand and the grasped objects represents the second methodology stage. Lastly, the third stage was achieved by designing a novel hybrid pressure-vibration-temperature feedback stimulation system to provide a huge information regarding the prostheses environment to the users without brain confusing or requiring long pre-training. The main contribution of this work is the development and evaluation of the first step of a novel approach for a lightweight, 7 Degrees-Of-Freedom (DOF) tactile prosthetic arm to perform an effective as well as fast object manipulation and grasping. Furthermore, this study investigates the ability to convey the tactile information about the contact pressure, surface texture, and object temperature to the amputees with high identification accuracy by mean of using the designed hybrid pressure-vibration-temperature feedback wearable device. An evaluation of sensation and response has been conducted on forty healthy volunteers to evaluate the ability of the haptic system to stimulate the human nervous system. The results in term of Stimulus Identification Rate (SIR) show that all the volunteers were correctly able to discriminate the sensation of touch, start of touch, end of touch, and

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grasping objects. While 94%, 96%, 97%, and 95.24% of the entire stimuli were successfully identified by the volunteers during the experiments of slippage, pressure level, surface texture, and temperature, respectively. The position tracking controller system was designed to synchronize the movements of the volunteers' elbow joints and the prosthetic's elbow joint to record the withdrawal reflexes. The results verified the ability of the haptic system to excite the human brain at the abnormal noxious stimulus and enable the volunteers to perform a quick withdrawal reflex within 0.32 sec. The test results and the volunteers' response established evidence that amputees are able to recover their sense of the contact pressure, the surface texture, and the object temperature as well as to perform thermal withdrawal reflexes using the solution developed in this work.

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Sistem stimulasi maklum balas hibrid yang dapat mengenal pasti tekanan sentuhan, tekstur permukaan, dan suhu pada masa operasi yang sama direka untuk tangan prostetik bagi memberikan sensasi sentuhan kepada pesakit amputasi. Di samping itu, sistem haptik telah dibina untuk membolehkan pengguna prostetik melaksanakan tindakbalas refleks yang disebabkan oleh rangsangan haba dengan pantas. Sensasi semula dicapai dengan merangsang sisa kulit anggota pesakit secara tidak-invasif, berdasarkan jenis dan tahap isyarat sentuhan yang diberikan oleh sistem deria prostesis. Oleh itu, tiga peringkat reka bentuk dan pembangunan telah dilakukan untuk memenuhi metodologi tesis ini. Reka bentuk alat prostatik secara sentuhan-vibro, yang direka bentuk untuk mengesan tekanan sentuhan dan tekstur permukaan di hujung atas, mewakili tahap metodologi pertama. Dalam pada itu, reka bentuk rangsangan hibrid tekanan-getaran yang baru bagi menyampaikan maklumat sentuhan tentang tekanan hubungan antara tangan prostetik dan objek yang dipegang mewakili tahap metodologi kedua. Akhir sekali, tahap ketiga dicapai dengan mereka bentuk sistem stimulasi maklum balas hibrid suhu-getaran-tekanan baru bagi memberikan lebih maklumat tentang persekitaran prostesis kepada para pengguna tanpa membingungkan otak atau memerlukan pra-latihan yang lama. Sumbangan utama kerja ini ialah pembangunan dan penilaian langkah pertama pendekatan baru untuk lengan prostetik yang ringan dengan 7 Darjah-Kebebasan (DOF) bagi melaksanakan manipulasi dan genggaman objek yang efektif. Selain daripada itu, keupayaan untuk menyampaikan maklumat sentuhan mengenai tekanan hubungan, tekstur permukaan, dan suhu objek dengan ketepatan pengenalan yang tinggi dari sudut maklum balas hibrid suhu-tekanan-getaran min peranti. Penilaian sensasi dan tindak balas telah dijalankan ke atas empat puluh subjek yang sihat untuk menilai keupayaan sistem haptik untuk merangsang sistem saraf manusia. Keputusan dari segi Kadar Pengenalan Rangsangan (SIR) membuktikan bahawa semua peserta dapat membezakan dengan tepat sensasi sentuhan, awal sentuhan, akhir sentuhan, dan genggaman objek. Walau bagaimana

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pun, 94%, 96%, 97%, dan 95.24% keseluruhan rangsangan telah berjaya dikenal pasti oleh para sukarelawan semasa percubaan gelinciran, tahap tekanan, tekstur permukaan, dan suhu, masing-masing. Sebaliknya, sistem pengawal kedudukan direka untuk menyelaraskan pergerakan sendi siku sukarelawan dan sendi siku prostetik untuk mencatatkan tindakbalas refleks. Dapatan kajian mengesahkan keupayaan sistem haptik untuk merangsang otak manusia tentang rangsangan yang tidak normal dan membolehkan para sukarelawan melakukan tindakbalas refleks yang cepat dalam masa 0.32 saat. Keputusan ujian dan tindak balas sukarelawan membuktikan bahawa pesakit kudung dapat mengembalikan rasa tekanan hubungan, tekstur permukaan, dan suhu objek, dan juga untuk melakukan tindakbalas refleks terma menggunakan penyelesaian yang dibangunkan dalam kerja ini.

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LIST OF ABBREVIATIONS

ADL	-	Activities of Daily Living
ADC	-	Analog-to-digital convertor.
AC	-	Alternating current.
ABS	-	Acrylonitrile Butadiene Styrene.
BBM	-	A Beam Bundle Model.
BLE	-	Bluetooth low energy.
CAC	-	Common anode configuration.
CEC	-	Concentric electrode configuration.
CUFF	-	Clenching Upper-limb Force Feedback device.
CA	-	Charge Amplifier.
CAD	-	Computer-aided design.
DOF	-	Degree of freedom.
DSP	-	Digital signal processor.
DC	-	Direct current.
DUT	-	Device under test.
EMG	-	Electromyogram.
ERM	-	Eccentric rotating mass.
EDR	-	Electrodermal response.
FSR	-	Force-sensing resistor sensor.
FTS	-	Frictional tactile sensation.

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FPCB	-	Flexible printed circuit board.
FTSA	-	Flexible tactile sensor array.
FSS	-	Feedback stimulation system.
FPC	-	Flexible printed circuit.
HHTTFSS	-	Hybrid haptic surface texture-thermal feedback stimulation system.
HHPVFSS	-	Hybrid haptic pressure-vibration feedback stimulation system.
IEEE	-	Institute of Electrical and Electronics Engineers.
IRB	-	Institutional review board.
IoT	-	Internet of Things.
IP	-	An Internet Protocol address.
LED	-	Light-emitting diode.
LRA	-	Linear resonant actuator.
MORPH	-	Moyelectrically – operated RFID prosthetic hand.
MR	-	Magnetic Resonance.
MRFs	-	Magnetorheological fluids.
MT	-	Mechano-tactile display.
NG	-	Nanogenerator.
NWR	-	Human nociceptive withdrawal reflex
PET	-	Polyethylene terephthalate.
PMMA	-	Polymathic methacrylate.
PVDF	-	Perpendicular polyvinylidene difluoride.
PWM	-	Pulse width modulation.
PID	-	Proportional, integral, and derivative controller

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QTC	-	Quantum Tunnelling Composite pressure sensor.
QOL	-	Quality Of Life.
RFID	-	Radio-frequency identification.
SIR	-	Stimuli Identification Rate.
SAMs	-	Southampton adaptive manipulation scheme.
SHP	-	Soft Hand Pro.
SD	-	Standard Deviation.
SEM	-	Scanning electron microscope.
TR	-	Targeted nerve reinnervation.
VCSEL	-	Vertical-Cavity Surface-Emitting Laser.
VT	-	Vibro-tactile display.
VLC	-	Visible Light Communication.

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LIST OF SYMBOLS

F_L - Load fitting function.

F_m - Load acts on the center of the palm.

F_m - Tangential force.

F_n - Maximum normal force.

F_t - Tensile force.

F_s - Upper arm gear tangential force.

H - Heavy pressure level.

$\vec{I}(t)$ - Index finger pressure sensor signal.

L - Light pressure level.

L_m - Distance from the center of the palm to the elbow pivot.

L_f - The index finger length.

l - Applied load.

L_s - Applying stander load.

M - Middle pressure level.

Ma - Matchstick surface.

$\vec{M}(t)$ - Middle finger pressure sensor signal.

M_f - Applied the moments.

M_s - Driving moment of the servomotor.

$\vec{P}(t)$ - Pinky finger pressure sensor signal.

$\vec{Pa}(t)$ - Palm finger pressure sensor signal.

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